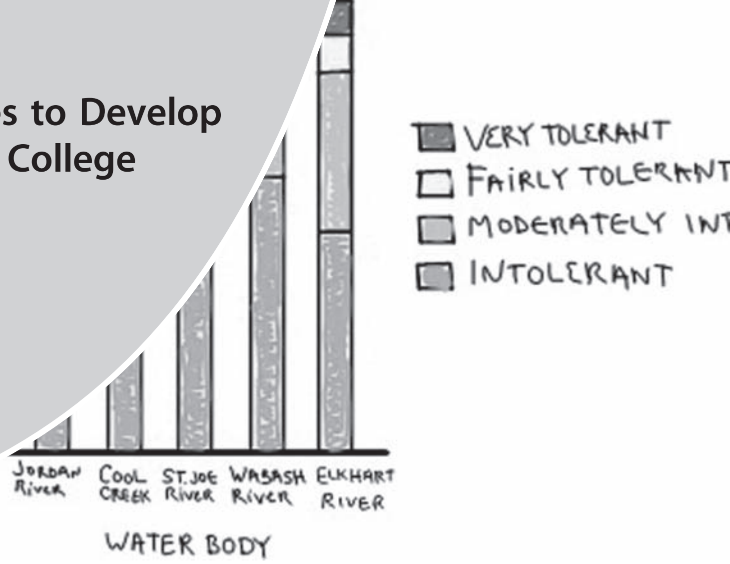
RESEARCH ON LEARNING

Instructional Strategies to Develop Graphing Skills in the College Science Classroom

JOSEPH A. HARSH, MIKAELA SCHMITT-HARSH



Abstract

Given the importance of succinctly communicating complex information, proficiency in graphing is a central element of scientific literacy. Evidence indicates that learners of all ages and levels of expertise have difficulties in displaying and reading visual data. Numerous studies have investigated the enactment of various activities to improve graphing in the college science classroom, but most of this work has focused on graphing difficulties and the implications of general instructional strategies as part of a semester-long curriculum. Few studies have discussed how specific interventions can be implemented to effectively hone graphing abilities. We evaluated (1) five key instructional features of an inquiry-oriented stream-ecology unit that consisted of data collection and graphing and (2) the unit's impact on non–science majors' analytical skills. Comparing pretest and posttest data, as well as a supplemental questionnaire, student responses demonstrated substantial positive impacts on graphing skills and attitudes toward graphing. The results also highlighted features of the unit that were considered successful. Although we a describe a particular stream-ecology activity, the framework and design features we present can be applied to other case studies and across disciplines.

Key Words: *Graphing; quantitative literacy; ecology; inquiry; stream macroinvertebrates.*

○ Introduction

Amid the explosion of data over the past 30 years, increasing emphasis has been placed on developing learners' facility with information visualizations to foster understanding of domain-specific knowledge and the successful navigation of everyday life (National Research Council, 1996). In the sciences, proficiency in graphing is considered a central element of scientific literacy, given the importance of succinctly communicating complex information (AAAS, 2011). The need for graph literacy is even more evident when considering that television and the Internet, currently the predominant sources of science and technology information (National Science Board, 2010), commonly present visual data that inform opinion on public policy and personal actions.

> *In the sciences, proficiency in graphing is considered a central element of scientific literacy.*

Despite this educational perception of graphing's importance and the ubiquitous positioning of data representations in daily life, it has been found that learners of all ages and levels of expertise, including the elementary student and scientist alike, have difficulties in summarizing, condensing, and displaying quantitative data (as reviewed by Glazer, 2011). At the undergraduate level, examinations of science and nonscience students' graph comprehension and conceptualization abilities have outlined specific weaknesses in areas that include variable identification and interpretation of variable relationships, utilization of the appropriate graph type, detection of data trends, and the ability to transform simple data into graphical form (Bowen et al., 1999; Picone et al., 2007; Bray Speth et al., 2010; Maltese et al., 2015). Similar difficulties have been likewise documented for secondary students (Tairab & Al-Naqbi, 2004) and graduate students (Harsh et al., 2013). Thus, given the persistence of common errors in graphing skills across the academic continuum, such findings question the effectiveness of traditional undergraduate science curricula in developing students' abilities to use and understand graphical data.

Because data display is an essential feature of scientific literacy, there is a developing catalogue of literature on the enactment of graphing instruction in the introductory science classroom. While prior research has demonstrated the usefulness of graphing-motivated exercises to improve analytical skills, most of this work has focused on students' graphing difficulties (e.g., Roth, 2004) and the implications of general instructional strategies (e.g., inquiry-based learning) as part of semester-long curricula (e.g., Picone et al., 2007; Bray Speth et al., 2010). Few studies have discussed how specific interventions can be designed and implemented to effectively hone students' graphing skills. Here, motivated by common graph-literacy

The American Biology Teacher, Vol. 78, No 1, pages. 49–56, ISSN 0002-7685, electronic ISSN 1938-4211. DOI: 10.1525/abt.2016.78.1.49.

issues seen in our research with undergraduates (Harsh et al., 2013; Maltese et al., 2015), we describe the design and implementation of a short-term unit that strongly emphasizes graphing theory and practice for use with introductory students. While the stream-ecology graphing unit (hereafter "SEGU") contextualizes the intervention within an on-campus water-quality module, the design framework is grounded in five key instructional features drawn from the literature that can be applied to course- and lab-based activities across disciplines to help advance secondary and college students' graphing skills.

○ Instructional Strategies to Develop Graphing Skills

As recognized in the literature, introductory major and nonmajor science courses often fail to effectively engage students meaningfully in the learning process (e.g., Seymour & Hewitt, 1997) as well as promote fundamental skills such as quantitative literacy (e.g., Picone et al., 2007). Further, it can be anticipated that many college science faculty likely overestimate their students' baseline understanding of graphing, which may result in the lack of instructional emphasis on how to convey visual information about complex scientific concepts (Bray Speth et al., 2010; Maltese et al., 2015). In response to this, prior research efforts on data display have offered a raft of design features for instructional strategies that actively advance students' abilities to draw and read graphs. These design features are often intended to be incorporated into inquiry-learning experiences with an ultimate goal of sponsoring both "hands-on" and "minds-on" opportunities for conceptual understanding. For the design and implementation of the SEGU, we focus our attention on five design features (discussed below and summarized in Table 1).

First, students should be exposed to data practices through experiences comparable to what practitioners in the field engage in. To that end, students are expected to develop graphing skills by actively participating in authentic scientific inquiry through the investigation of realistic and contextualized problems (Bowen & Roth, 2005). According to Morrison and McDuffie (2009, p. 31), students "should be challenged to . . . be able to analyze and interpret the data they collect, and propose descriptions and explanations based on their data." An array of positive outcomes have been attributed to authentic experiences in which students are meaningfully and purposefully engaged in representing collected data. For example, research efforts on secondary and college science students' data analysis skills have suggested that the collection and analysis of contextualized "real" data is positively associated with the transformation of raw data and graph interpretation (Picone et al., 2007; Morrison & McDuffie, 2009; Bray Speth et al., 2010). Thus, given the centrality of data representation to the scientific enterprise (Roth & McGinn, 1998; Grumbine, 2010), we advocate that designs for graph-learning activities take authentic data practices into account.

A second key characteristic identified in the literature is that students should gain exposure to complex or "messy" data and data representations for the development of advanced graphing skills, because data (and, by extension, graphs) that are complex reflect the genuine nature of research in the science domain. However, students are often enculturated in graphing practices that use "clean" or "simple" data for the demonstration of predetermined outcomes or trends (Bowen & Roth, 2005). Work by Bowen and Roth (2005) with preservice teachers suggests that such experiences with "clean data" may contribute to misconceptions regarding the level of relationships between variables needed to make scientific claims. Moreover, Picone et al. (2007) found that students often "struggled amidst statistical noise in data" and thus recommended that greater emphasis be placed on instruction using complex data and graphs. To that end, and in contrast to "cookbook" activities in which students are often ritualistically guided in the construction and interpretation of simple data sets, the generation and analysis of complex data may be seen as a means to enhance students' advanced graphing skills.

Third, students should be guided in data display through learning interventions that rely on traditional (i.e., pen and paper) and technological representation practices in contribution to data skills (Roth & McGinn, 1997; Tairab & Khalif Al-Naqbi, 2004). In a two-step design, students (a) initially transform data by hand into a representation as a means to foster cognitive skills and then (b) use technological tools (e.g., computers or graphing calculators) to visualize data and variable relationship for interpretive purposes. Through such an approach, it is posited that students become fully engaged in cognitive practices, developing "hands-on, minds-on skills to construct graphs" (Tairab & Khalif Al-Naqbi, 2004, p. 130).

Table 1. Description of the five design features utilized in the SEGU.

Design Feature	Description
1. Collection of authentic data	Students should be active participants in authentic scientific investigations of realistic and contextualized problems.
2. Exposure to complex data	Students should be exposed to, and encouraged to engage with, complex data sets that reflect the genuine nature of research.
3. Two-step data analysis approach	Development of graphing skills should proceed using a two-step design that first engages students' cognitive processes and then uses technology for visualization purposes.
4. Explicit graphing instruction	Students' proficiency gaps should be attended to by using explicit teaching instruction or "modeling" of graph skills.
5. Collaborative graphing practices	Students should work collaboratively to make sense of and effectively communicate data.

Fourth, formal instruction of data transformation and interpretation skills should be explicitly introduced to students through classroom practice. Although proficiency is expected to be enhanced through the features described above, a number of researchers have indicated that college students may continue to hold naive or incomplete graphing skills despite such interventions (e.g., Bray Speth et al., 2010). As a result, various authors have emphasized the role of explicit teaching instruction or "modeling" to attend to proficiency gaps (Picone et al., 2007; Taylor, 2010). The practice of teacher modeling creates an opportunity for students to gain insight into how and why raw data sets might be transformed or operationalized and interpreted in a given manner (Bowen & Roth, 1998). Given documented student difficulties, particular instructional focus should be placed on helping students in the hierarchical steps of (a) reading the data (how to extract information from specific data points), (b) reading between the data (how to find trends and relationships in the data), and (c) reading beyond the data (how to draw inferences from the data; Curcio, 1987).

Finally, in line with conventional inquiry learning, data analysis interventions should be predicated on a cooperative environment where knowledge is socially negotiated (Brown et al., 1989). Extensive social interactions allow students the opportunity to gain proficiency in using metacognitive and cognitive strategies for the effective transformation, interpretation, and communication of data. As advocated by multiple researchers (e.g., Roth & McGinn, 1997; Morrison & McDuffie, 2009), community discourse that is appropriately situated and directed can act as a bridge for students to gain a deeper conceptual understanding of graphing practices, and of the scientific enterprise more broadly.

These five design features were used in the SEGU, as described below. They can be applied to other units and across disciplines.

○ Course Organization

The general-education science course that included the SEGU was designed to introduce students to the fundamental principles and practices of the scientific enterprise. Offered on a per-semester basis at a large public university in the Midwest, the three-credit course (meeting 115 minutes, twice a week) collaboratively engages students in hands-on activities to develop their inquiry process skills and understanding of science within a broader context of environmentally relevant topics (e.g., climate change, water and soil quality). Although the class is open to all students during their college careers, most enrollees are underclassmen, preservice elementary educators. Multiple sections of the course are offered each semester, taught by graduate students and faculty, with an average class size of 20 students.

○ Organizing the SEGU Activity

Based on the design features above, the SEGU activity is intended to help nonscience students develop data representation skills as they relate to the construction and interpretation of graphs. In this short-term lab unit, students made use of collected benthic macroinvertebrate data to assess the water quality of an on-campus stream. Graphing activities were combined with stream sampling in an effort to expose students to hands-on practices in which they could become meaningfully and purposefully engaged in data collection and analysis. It was anticipated that the topic would be relatively approachable across levels of science expertise, given that most students are familiar with streams and/or with environmental issues often associated with water quality (e.g., pollution). In addition, situating the activity in a local environment (e.g., an on-campus stream) not only allows access to resources, but likely contributes to personal relevance and interest for the students.

During the first part of the unit, students were broadly introduced to the topic of water quality and how benthic macroinvertebrates can be used as biological predictors of stream health. Working in groups of three or four, students collected and identified macroinvertebrates from the on-campus stream, using the sampling protocol and taxonomic keys from the Hoosier Riverwatch manual (Indiana Department of Natural Resources, 2011). This manual provides information regarding the relative tolerance of each macroinvertebrate species to pollution, enabling students to quantify an index value that assesses the general health of the stream being sampled. For a more detailed description of techniques for sampling stream benthic macroinvertebrates, see McDonald et al. (1991).

In the second part of the unit, students used stream data (e.g., species diversity, pollution tolerance indices) collected across course sections and across semesters to generate multiple graphs, in order to investigate the water quality of the on-campus stream. For this, students worked in groups of two to conceptualize multiple graphs that demonstrated the data captured at the section, semester (across course sections), and course (across sections over multiple semesters) levels. Using a two-step approach, groups first transformed by hand the data they had collected and then used graphing software to visualize those data along with data collected at the section, semester, and course levels. In support of this task, students were given an assignment in advance that was centered on a reading about graph design (Kosslyn, 1994) and a computer-based tutorial on using Excel to generate graphs (Microsoft, n.d.). Additionally, a short (20–25 minute) discussion was used at the beginning of class to examine the main ideas of the readings, introduce aspects of data display and interpretation, and model how to handle visual data. Upon completion of the day's activity, groups were encouraged to reflect on the appropriateness of their graphical representation and formulate general conclusions as part of a whole-class discussion. Knowing the sampling protocol and collected data, students were then able to use their representations as evidence regarding the relative health of the stream system, and to demonstrate the value of replicates in data collection.

During the third part of the unit, students worked in groups of two to compare the water quality of the on-campus stream to that of statewide water bodies. Using a large macroinvertebrate data set (>250 cases) compiled in advance from the Hoosier Riverwatch website (Indiana Department of Natural Resources, 2011), groups were tasked to construct graphs that provided evidence of the health of streams in different watersheds. Microsoft Excel was again utilized for this task, given its previous application in class and the assigned readings and tutorials associated with it; alternative graphing-software visualization tools could be used that align with other course formats and intents. This exercise enabled students to gain experience in manipulating complex (or "messy") spreadsheet data and in selecting information to graph that they considered relevant to the inquiry. Once the data had been plotted, the groups were encouraged to reflect on the appropriateness of their graph and the patterns or trends in water quality being demonstrated – again subsequently discussed as a class.

As an outcome for this unit, students were assigned to write a hypothetical article for a scientific journal discussing the health of the on-campus stream, comparable to scholarly writings in publications such as *Scientific American* or *Discover*. Students were asked to include a description of the intent of the study, the value of the assessment, the methodology involved, and the outcomes of the study. Given the data-representation foci of the activity, emphasis was placed on the students' use of the constructed graphs as evidential support for their general conclusions. In agreement with E. O. Wilson's (2002) supposition that science is most effectively communicated as a story, students were encouraged to write in a creative and informative manner that would be approachable to scientists and the general public alike.

○ Analysis of the SEGU Activity

Data were collected in spring 2012 to assess the influence of SEGU on developing students' data skills. Permission was obtained from the university's Institutional Review Board, and students were given an information sheet detailing the project prior to the voluntary completion of pretests and posttests, as well as a questionnaire focused on the effectiveness of the SEGU. The pretests and posttests were completed by nonscience majors (n = 40), all first- or second-year students, in two sections taught by the first author. Prior to the start of the SEGU, students in both sections were asked to complete a 10-item test to assess their baseline graphing skills and self-reported attitudes about graphing. In line with Picone et al.'s (2007) recommendations, pretest items were designed to focus on the development of a short list of central graphing skills and were based on subjects that students had some familiarity with or that could easily be explained on a test. The test incorporated graph-based tasks from existing validated instruments, with minor modifications for the given classroom population (e.g., changes in question context to ensure understanding), designed to measure college students' abilities to read and draw graphs (Picone et al., 2007; Bray Speth et al., 2010; Maltese et al., 2015). Upon completion of the SEGU, students were asked to answer a posttest consisting of questions that were akin to, and matched with, items on the pretest. For evaluative purposes, graph drawings were blindly rated by the first author, who has substantial experience in assessing graph literacy skills, using a vetted scoring rubric (Harsh et al., 2013) based on Kosslyn's (1994) graph framework (e.g., graph type, variable placement), content (e.g., scaling, data positioning), and labeling (e.g., title, axis labels). Graph interpretation responses and graph construction rationales were also scored for appropriateness (e.g., proper association of graph and data type). Instead of using identical pretest and posttest items that might have resulted in simple replication, comparable pretest and posttest items were matched to gauge changes in students' graphing responses (for example matched questions, see Figure 1). Pretest and posttest data were assessed using paired t-tests conducted with IBM SPSS version 19.

Additionally, students were invited to anonymously complete a brief (13-item) questionnaire in which they were asked to rate

Pretest Question

Scenario/Problem:
A species of fish lives only in deep lakes. You predict that food limits this species to deep lakes, and you want to test that hypothesis. In aquaria, you feed the fish food from deep lakes where it normally lives and feed them food from shallow lakes, and compare how well they grow and reproduce in each treatment.

Data:

Number of Eggs Per Female		
Replicate	Deep Lake Food	Shallow Lake Food
1	25	14
2	19	11
3	21	16
4	28	10

Posttest Question

Scenario/Problem:
You are interested in whether an organic fertilizer is as effective as conventional fertilizer in the fruiting of apple trees. You predict that the organic and conventional fertilizers will yield a comparable number of apples, and you want to test that hypothesis. In an orchard, you fertilize apple trees with the same amount of the different fertilizer types and compare how well they grow and reproduce (fruit) in each treatment.

Data:

Number of Apples Per Tree		
Replicate	Organic Fertilizer	Conventional Fertilizer
1	250	140
2	190	110
3	210	160
4	280	100

Figure 1. Example of matched pretest and posttest items used to assess the development of students' graphing skills. The students were asked to (**A**) construct a graph from the provided data, (**B**) interpret any trends in the plotted data, and (**C**) provide a rationale for the graph type used to represent the data. The pretest question was modified from Picone et al. (2007).

(a) their overall satisfaction with the SEGU and (b) how they thought the unit, and its associated components, contributed to the development of their graphing skills. Each aspect was rated on a scale from 1 (none or very little) to 4 (a great deal) and assessed using descriptive statistics. An open-ended question was also included, to solicit the students' overall impressions of the unit and any specific components they liked or identified as affecting learning the "most" or "least."

○ Results & Interpretations

Of the 40 students in the two course sections, 37 (92.5%) completed both the pretest and the posttest, and 39 (97.5%) completed the supplemental questionnaire regarding their perceptions of the SEGU. Analysis of the pretest and posttest data indicated that, overall, students made significant gains in graphing skills through the short-term SEGU (Table 2). The results also revealed positive impacts of the individual unit activities on student learning and other affective considerations.

Graph Construction

Significant improvements were documented in the students' aptitudes to transform data graphically upon completion of the unit (Table 2). The results indicated that students made substantial gains in the areas of content representation (i.e., the accuracy of the data being plotted) and labeling (i.e., scaling, indication of variables, and units of measure). In addition to the physical display of data, significant effects were noted in students' conceptual understanding of graph design. At the end of the unit, students were more likely to provide rationales for axis formatting that referenced both conventional variable positioning (e.g., independent variable on the x-axis) and variable relationship; whereas, before the unit, they were more likely to reference traditional placements and/or personal preference (i.e., "what makes sense to me"). Likewise, students' reasoning for selecting given graph types to display data significantly shifted from that of personal preference and visualization (i.e., "easy to see what is being graphed") toward the conceptualization of variable relationships and data types. One student comment from the supplemental questionnaire particularly

Table 2. Pretest and posttest scores of students' (n = 37) graph data transformation and comprehension skills, and affective responses to graph data (paired t-tests; 95% confidence intervals shown in parentheses). When multiple test items were used to measure comparable skills, those items were grouped for analysis (as noted in parentheses).

Item	Point Value Possible[a]	Pretest Mean (± SD)	Posttest Mean (± SD)	P
Graph Drawing Skills				
Reasoning for variable positioning in graph construction	2	0.64 (0.5)	1.15 (0.5)	0.000
Reasoning for using the employed graph type to represent the data (n = 2 questions)	4	2.01 (0.5)	2.58 (0.8)	0.000
Transformation of Data into Graphs (n = 2 questions)				
Framework items (i.e., graph type, axial layout, variable positioning)	10	9.12 (1.0)	8.74 (0.9)	0.109
Content items (i.e., accuracy of data, effective data representation)	8	6.61 (1.2)	7.47 (0.7)	0.000
Label items (i.e., proper identification of variables, labels, scale)	13	7.04 (1.7)	10.90 (1.5)	0.000
Graph Reading Skills				
Identification of independent and dependent variables	2	1.49 (0.1)	1.65 (0.8)	0.384
Interpretation of graphs demonstrating single-variable relationships (n = 2 questions)	2	1.54 (0.5)	1.88 (0.3)	0.000
Interpretation of a graph demonstrating mathematical concepts (i.e., slope)	1	0.11 (0.3)	0.11 (0.3)	1.0
Affect				
Level of anxiety when faced with graph data[b]		2.32 (0.8)	2.05 (0.6)	0.010
Level of frustration when faced with graph data[b]		2.19 (0.8)	1.95 (0.7)	0.010

[a]Maximum potential score for the given skill. Graph-drawing skills were evaluated from the pretests and posttests using an existing scoring rubric (Harsh et al., 2013), and graph-reading skills were evaluated on the basis of response correctness.
[b]Items measured on a 4-point scale: 0 = lowest, 4 = highest.

espouses this view: "I learned a lot about data collection and graph making. I knew how to create graphs in Excel before, but now I understand why we use certain types of graphs" (Student A). Students largely agreed that the unit helped develop their graph-drawing skills, giving that statement an average score of 3.2 on a four-point scale (1 = lowest, 4 = highest). Such results suggest the utility of the unit in fostering students' practical and theoretical knowledge in transforming raw data into graphical representations.

Graph Interpretation

Student responses on the pretest, posttest, and supplemental questionnaire revealed mixed outcomes with regard to graph interpretation. As seen in Table 2, results from the posttest data revealed significant gains in the higher-order skill of identifying global (i.e., "big-picture") patterns in graphs displaying single-variable relationships. Inasmuch, students rated the average contribution of the SEGU at 3 (out of 4; 1 = lowest and 4 = highest) in helping develop their graph interpretation skills. However, these results are complicated, given that student responses also indicated persisting general difficulties in the interpretation of more sophisticated graphs that required mathematical functions (i.e., the determination of slope). In light of this, it may be of particular value in future implementations of the framework to place greater emphasis on teaching students how to read "complex" data displays that involve multiple variables or mathematical functions.

Student Satisfaction, Attitudes toward Graphing, & Effectiveness of SEGU Design

In addition to assessing change in graphing skills, the pretest, posttest, and questionnaire invited students to rate their attitudes toward graphing (i.e., anxiety and frustration), satisfaction with the learning unit, and how they felt the associated SEGU activities affected their learning. Students were found to report significantly lower levels of both anxiety and frustration when presented graph data upon completion of the unit (Table 2).

Overall, the responses to the SEGU reported in the supplemental questionnaire were largely positive (Table 3). On a four-point scale (1 = unsatisfied/no contribution, 4 = very satisfied/high contribution), students rated their satisfaction with the learning unit at 3.3, as represented by comments in the open-response section: "I really enjoyed this unit. It was something I never looked into or had studied before, but the amount of graphing and interpretation we did was very beneficial" (Student B). As a means to gain a better understanding of the efficacy of the SEGU design, students were asked to report how the various unit activities and features contributed to their learning (see Table 3). Students overwhelmingly identified the collection of their own data as a strong contributing factor to the development of graphing skills (3.5). More specifically, in open response, students often commented on the particular value of this element in providing the opportunity to take an active role in collecting meaningful data they had a strong grasp of. As an example, one student commented: "I liked being able to collect the data on our own and then work with it. Many times when working with graphs you deal with data that is not familiar to you. The hands-on work really gave me a better understanding of the project" (Student C). Likewise, working in small groups (3.5), discussing how they represented data as a class (3.5), and the use of Excel as a tool to visualize data (3.4) were rated by students as contributors to the development of graph skills. Working with data at multiple levels (i.e., class level, across course sections, and the

Table 3. Student responses (n = 39) to the supplemental questionnaire questions regarding general perceptions of the SEGU and the contributions of the various unit components to learning. Mean Likert scale (1 = low satisfaction/contribution, 4 = high satisfaction/contribution).

Questionnaire Item	Mean Likert Score
Overall satisfaction with the SEGU	3.3
Helped develop graph construction skills	3.1
Helped develop graph interpretation skills	3.0
Contributions of using data at different levels (i.e., class, semester across sections, and across semester) to recognize data patterns	3.2
Contributions of the Indiana DNR Hoosier Riverwatch data set to the ability to use real or "complex" data	3.3
Contributions to the following SEGU features to understand graph construction and interpretation:	
i. Collection and use of your own data	3.5
ii. Discussing how each group represented data as a class	3.5
iii. Working in small groups	3.5
iv. Using a graphing program	3.4
v. Using a two-step approach where graphs were first drawn by hand and then input into a graphing program	2.8
vi. Reading and discussing the assigned reading about graph design	2.8

large "raw" data set from the Hoosier Riverwatch website) were, as well, reported to contribute to students' ability to identify data trends (3.3) and use "real" data (3.2).

The two lowest-rated features of the SEGU were the two-step graphing approach, in which students were asked to sketch the graph first by hand and then input it in Excel for visualization (2.8), and the graph-design reading assignment (2.8). While it is not possible to offer a direct rationale for these marginally lower ratings, because students did not explicitly address these features in the open-response section, two possible explanations can be offered for these phenomena. First, as noted in classroom observation, students intimated that the two-step approach of continuously drawing the graphs by hand prior to generating them electronically was a bit "tedious" and "time consuming." Second, in classroom discussion, while most students indicated finding the graph-design article useful, a small group mentioned that they found the reading to be "dry" or "repetitive" because they thought they had prior experience with the topics. As with most learning activities and assignments, such types of "negative" responses are to be anticipated to a given degree.

○ Conclusions

Given the increasing need for all citizens to understand an increasing volume of data presented in visual forms on a daily basis, educational interventions that promote graphing skills are of particular importance. Although the small sample size (n = 37) for implementing this SEGU activity may limit result generalizability, the early findings presented here provide evidence that short-term contextualized graphing interventions based on the five design features (Table 1) can be an effective instructional tool to enhance introductory college science students' graphing skills. Despite the relatively short duration of the SEGU, students demonstrated substantial improvements in their abilities to transform and comprehend graph data. Additionally, students reported significant positive impacts on their attitudes toward graphing and provided overwhelmingly positive responses with regard to their level of satisfaction with the SEGU and its contributions to learning. But while the interventional outcomes were encouraging, it was the students' low pretest baseline of fundamental graph knowledge that was "eye opening." Current recent research indicates that college educators should not simply assume that students have a set of adequate graphing skills based simply on their academic standing. Although the SEGU activity requires the investment of multiples days – a fact that may be constraining, given the curricular obligations of introductory science courses – a strong argument can be made for the essential nature of instructional practices that not only utilize graphical forms of data but also explicitly focus on the development of graph skills to prepare students for later science coursework and to promote scientific literacy in our citizenry.

The framework described here could be adapted to meet the needs of a diverse range of secondary and college science classrooms. As an example, the SEGU has been amended for use in a lecture-based (75-minute) introductory environmental science course as a two-day unit, focused on water quality, with 45 students. Further, while the system of study described here was a local stream, future iterations of such short-term graphing units could be centered on a wide range of topics relevant to course goals and/or to students' daily lives (e.g., soil quality, urban ecology, biodiversity). Future iterations of a similar graphing activity would benefit from the inclusion of a larger student sample as well as a comparison group to more appropriately characterize the effectiveness of such interventions in enhancing college science students' graphing skills. Additionally, while the SEGU was nested in the topic of water quality, the potential influence of this unit on students' ecological knowledge (i.e., water quality) or environmental worldview (Cawthorn et al., 2011) was not examined. Further research, as well as supplemental instruction, could attempt to assess and develop student knowledge and behaviors associated with the overlying topic.

○ Acknowledgments

We gratefully acknowledge Adam Maltese for his contributions to the development of this project and his efforts in reviewing the manuscript. In addition, we thank Gayle Buck, Christina Melki, Khadija Fouad, Banu Erumit, Mary Mills, and Susan Hawkins for their feedback in the SEGU design process.

References

AAAS (2011). *Vision and Change in Undergraduate Biology Education: A Call to Action.* Washington, DC: AAAS.

Bowen, G.M. & Roth, W.-M. (1998). Lecturing graphing: what features of lectures contribute to student difficulties in learning to interpret graphs? *Research in Science Education*, *28*, 77–90.

Bowen, G.M. & Roth, W.-M. (2005). Data and graph interpretation practices among preservice science educators. *Journal of Research in Science Teaching*, *42*, 1063–1088.

Bowen, G.M., Roth, W.-M. & McGinn, M.K. (1999). Interpretations of graphs by university biology students and practicing scientists: toward a social practice view of scientific presentation practices. *Journal of Research in Science Teaching*, *36*, 1020–1043.

Bray Speth, E.B, Momsen, J.L., Moyerbrailean, G.A., Ebert-May, D., Long, T.M., Wyse, S. & Linton, D. (2010). 1, 2, 3, 4: infusing quantitative literacy into introductory biology. *CBE Life Sciences Education, 9*, 323–332.

Brown, J.S., Collins, A. & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher*, *18*, 32–42.

Cawthorn, M., Leege, L. & Congdon, E. (2011). Improving learning outcomes in large environmental science classrooms through short-term service-learning projects. *Journal of Environmental Studies and Sciences, 1*, 75–87.

Curcio, F.R. (1987). Comprehension of mathematical relationships expressed in graphs. *Journal for Research in Mathematics Education, 18*, 382–393.

Glazer, N. (2011). Challenges with graph interpretation: a review of the literature. *Studies in Science Education, 47*, 183–210.

Grumbine, R. (2010). Using data-collection activities to enrich science courses. *American Biology Teacher, 72*, 369–372.

Indiana Department of Natural Resources (2011). Hoosier Riverwatch, volunteer stream monitoring training manual. Available online at http://www.in.gov/idem/riverwatch/files/volunteer_monitoring_manual.pdf.

Harsh, J.A., Maltese, A.V. & Warner, J.M. (2013). The development of expertise in data analysis skills: an exploration of the cognitive and metacognitive processes by which scientists and students construct graphs. American Association for the Advancement of Science (AAAS) National Meeting, Boston, MA.

Kosslyn, S.M. (1994). *Elements of Graph Design.* New York, NY: Freeman.

Maltese, A.V., Harsh, J.A. & Svetina, D. (2015). Data visualization literacy: investigating data interpretation along the novice–expert continuum. *Journal of College Science Teaching, 45*, 84.

McDonald, B.S., Mullins, G.W. & Lewis, S. (1991). Macroinvertebrates as indicators of stream health. *American Biology Teacher, 53,* 462–466.

Microsoft (n.d.). How to create a basic chart in Excel 2010. Microsoft Office Training. Available online at http://office.microsoft.com/en-us/excel-help/how-to-create-a-basic-chart-in-excel-2010-RZ102559017.aspx.

Morrison, J. & McDuffie, A.R. (2009). Connecting science and mathematics: using inquiry investigations to learn about data collection, analysis, and display. *School Science and Mathematics, 109*, 31–44.

National Research Council (1996). *National Science Education Standards*. Washington, DC: National Academy Press.

National Science Board (2010). *Science and Engineering Indicators 2010*. Arlington, VA: National Science Foundation.

Picone, C., Rhode, J., Hyatt, L. & Parshall, T. (2007). Assessing gains in undergraduate students' abilities to analyze graphical data. *Teaching Issues and Experiments in Ecology, 5*. Available online at http://www.esa.org/tiee/vol/v5/research/picone/article.html.

Roth, W.-M. (2004). Emergence of graphing practices in scientific research. *Journal of Cognition and Culture*, *4*, 595–627.

Roth, W.-M. & McGinn, M.K. (1997). Graphing: cognitive ability or practice? *Science Education, 81*, 91–106.

Roth, W.-M. & McGinn, M.K. (1998). Inscriptions: toward a theory of representing as social practice. *Review of Educational Research, 68*, 35–59.

Seymour, E. & Hewitt, N.M. (1997) *Talking About Leaving: Why Undergraduates Leave the Sciences, vol. 12*. Boulder, CO: Westview Press.

Tairab, H.H. & Khalaf Al-Naqbi, A.K. (2004). How do secondary school science students interpret and construct scientific graphs? *Journal of Biological Education, 38*, 127–132.

Taylor, M.F. (2010). Making biology teaching more "graphic." *American Biology Teacher, 72,* 568–571.

Wilson, E.O. (2002). The power of story. *American Educator, 26,* 8–11.

JOSEPH A. HARSH is an Assistant Professor in the Department of Biology, James Madison University, 951 Carrier Dr., MSC 7801, Harrisonburg, VA 22807; e-mail: harshja@jmu.edu. MIKAELA SCHMITT-HARSH is an Assistant Professor in Interdisciplinary Liberal Studies, James Madison University, Maury Hall, MSC 1105, Harrisonburg, VA 22807; e-mail: schmi2ml@jmu.edu.